THE MGS AVIONICS SYSTEM ARCHITECTURE: EXPLORING THE LIMITS OF INHERITANCE

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ABSTRACT

This paper will discuss the architecture of the MGS Avionics System, which includes much of the electronics on-board the spacecraft: Electrical Power, Attitude and Articulation Control, Command and Data Handling, Telecommunications, and Flight Software. The overall system architecture was driven h y mission design, cost, and schedule demands resulting in a mix of inherited components and ncw designs. l'here is extensive usc of the inherited MO flight hardware (properly modified to accommodate ncw mission parameters and to remedy problems uncovered by the MO failure review hoards) and flight software/firmware. While the inheritance is high i n some areas, it is low in others. 'l"his paper will discuss the final MGS avionics design, and highlight some of the factors that drove the decision process, the assumptions made, problems encountered, and the risks associated with those decisions. The limits of inheritance and to what extent this experience fits into the context for NASA's "faster, better, cheaper" paradigm arc reviewed.

INTRODUCTION

August 21, 1993 was a disappointing day for this nation's planetary space program as controllers at JPL waited in vain for a radio signal from the Mars Observer (MO) spacecraft after pressurization of its propulsion system in preparation for injection into Mars orbit. This was to have been the long awaited return to the Red Planet since two Viking Landers settled onto Martian soil in 1976 and communications ceased in November 1982. The cause of the failure was investigated by three review boards. The most probable cause among several candidates was a catastrophic failure of the propulsion system. The loss of MO meant also the loss of critical observations of Martian geoscience and climatology necessary to answer key questions about its evolution, climate, and atmosphere of the most earth-like neighbor in our solar system. Interest in Mars remains high and because the lost science is essential to support future plans for the exploration of Mars, NASA approved the Mars Global Surveyor (MGS) Project with the requirement that it accomplish i(s objectives at a fraction of the MO cost.

The MGS project plan is to recover most of the MO science lost while applying NASA's ncw "faster, better, cheaper" paradigm. To accomplish these twin objectives (recover the science for fewer dollars) the Project was driven to a lower performance launch vehicle with a drastically reduced spacecraft mass. Only six of MO's eight instruments will be accommodated, leaving the Gamma Ray Spectrometer (GRS) and the Pressure Modulator Infra-Red Radiometer (PMIRR) to be carried by future Mars missions.

A reduced mass spacecraft forces a mission design that requires a significant reduction in fuel load. To accomplish this MGS will require aerobraking in the Martian atmosphere to establish the proper orbit. The first aerobraking experiment was late in the Magellan mission at Venus to circularize its orbit for gravity measurements after completing its primary mapping mission. However, MGS will be the first planetary mission to usc this technique as a fundamental requirement for mission success, i.e., successful management of the aerobraking phase prior to start of the mapping mission is essent ial to obtain the correct orbit for science investigations. To keep cost within bounds and meet the two year start-to-launch schedule required extensive usc of spare MO hardware for both engineering and science subsystems. However, usc of these assemblies, which were built for a heavier spacecraft, con flicted with the lower mass requirements and some replacement hardware ha. been required. Like MO, the MGS spacecraft is a single-poin[-failure tolerant design requiring redundant systems and sophisticated onboard fault protection. 1 ligh reliability Grade 1 parts arc used with fcw exceptions. The s ystem contractor is Lockheed-Martin Astronautics (LMA), Denver, who was awarded a system contract in July 1994 and is responsible for the spacecraft design, integration, test, and operation. The launch window for MGS opens on November 5, 1996, only 28 months after the start-of-contract.

MISSION DESCRIPTION

The launch window is just 21 days (MGS must get off during that period or wait another two years for the next favorable earth-Mars alignment). After launch, the cruise to Mars takes about 10 months with Mars orbit insertion burn in September, 1997. By January 20, 1998, aerobraking will have collapsed the initial 48 hour elliptical capture orbit down to a 2 hour circular mapping orbit at 378 Km above the planet's surface. A transition phase lasting until March 1998 will allow adjustment to the sun-synchronous 2:00 PM orbit required by the science investigation team. Mapping will begin in March 15, 1998 and will continue for a full Martian year until January 31, 2000. During mapping, the science platform is continuously nadir pointed. For the following three years, MGS will support the relay phase of the mission where the spacecraft will provide vital communications services for other missions to the planet's surface.

AVIONICS SYSTEM

The Avionics System of the MGS spacecraft includes Electrical Power Subsystem (13'S), Attitude and Articulation Control Subsystem (AA(X), Command and Data 1 landling Subsystem (C&DH), and Telecommunications Subsystem (Telecom). With a different space.aafl and launch vehicle, some changes in subsystem elements were required, while mass, cost, and schedule remain tbc major Project drivers.

Electrical Power Subsystem

Like MO, MGS will usc solar arrays for power generation, but unlike MO, MGS's aerobraking requirement drives the spacecraft to a symmetrical panel configuration in order to control the vehicle's aerodynamic characteristics during atmospheric drag passes. So MGS has two symmetrical solar arrays in place of MO's single array, Launch off of a Delta II vehicle severely limits the spacecraft envelope compared with MO, which launched from the larger Titan 111, This constrained the maximum size of the solar arrays to that which would fit within the Delta shroud. Countering this is a requirement for as much area as possible to increase aerodrag while minimizing heat build up. The worst case temperatures generated by aerobraking can raise the panel to the neighborhood of 200"C, which required a change in bonding materials from that originally proposed. Adding to this is the required cell area to produce at least 660 watts of power at aphelion during the mapping mission. The intersection of these three requirements resulted in a panel design that is half silicon and half gallium arsenide on germanium. MGS will be the first planetary spacecraft to usc this fragile but higher efficiency GaAs/Ge technology for power generation.

Complicating the solar array design was the requirement to have a magnetically Clean environment for the sensitive magnetometers located at the outboard end of each array. Special wire dressing was used to cancel magnetic fields caused by conductor currents. Finally, a careful measurement of the residual fields was made to assure the magnetometer investigator that the operation of the panels would not interfere with his instrument.

Reducing spacecraft mass required a shift from the long used and reliable nickel-cactmium batteries flown on MO and past planetary missions to a relatively ncw nickel-hydrogen technology. With hydrogen gas as onc of the electrodes, the cells are packaged in a pressure vessel designed to handle in excess of 2000 psi. Each of the two 20 Ampere Hour batteries is made Up of eight Common Pressure Vessels (CPV) with two cells in each vessel for a total of 16.

The flight spare Power Supply Electronics (PSE) and Battery Charge Assembly (BCA) were modified 10 improve robustness against single-point-failures identified by the MO failure review boards. Residual Power Shunt Assemblies (PSA) are used with only slight modification. Power distribution on the MGS spacecraft is 28 volts direct current, A C1'V life test program has been started to evaluate proper charging strategies and to determine depth-of-discharge cycles versus capacity 1oss for this design. Spacecraft power management strategies will be modified to accommodate the nickel-hydrogen battery characteristics, which differ from the MO nickel-cadmium experience base.

Attitude and Articulation Control Subsystem

The AACS provides attitude knowledge through the usc of the Celestial Sensor Assembly (CSA) which is a star scanner, two-axis Sun Sensor Detector assemblies, (S S1>), and a Mars I Iorizon Sensor Assembly (Ml ISA), which is used only during mapping, In addition, an Inertial Measurement Unit (IMU) containing three two-axis gyros provides integrated rate information between celestial measurement updates. Attitude control uscs four Reaction Wheel Assemblies (RWA) for fine control (the fourth wheel is skewed to allow it to back up any onc of the three primary wheels) rind thrusters for momentum desaturation. AA(X controls all propulsion system valving including main engine firing for Mars Orbit Injection, as well as three two-axis gimbals for articulation of the two solar panels and the 1 ligh-Gain Antenna (I IGA).

There were two major challenges for the AACS design: injection stage separation and aerobraking. MO injected using the Transfer Orbit Stage (TOS), a three-axis stabilized booster that allowed attitude control to pass smoothl y from the 1 'OS control system to the spacecraft, in contrast, MGS will be injected off a spinning upper stage. After the injection burn is complete, a yo-yo system is deployed from the upper stage to despin from about 60 to near zero rpm. Because the despin happens in just three revolutions, there is still substantial momentum stored in the spinning fuel with an indeterminate time period for spin down. As a result, the final spin rate about the z-axis could exceed gyro saturation for an unknown period of time. This coupled with an unfavorable lip-off rate could cause the spacecraft to rotate into the sun-exclusion zone and imperil the instruments before wc arc able to bring the spacecraft under control and reorient it away from the sun, The IMU has been modified to increase its rate capture range from six to 12 deg/see, and AACS has developed a strategy to bring the spacecraft under control before endangering the instruments with the existing complement of hardware,

During drop testing of the propellant tanks, it was discovered that a particular circulation pattern in the tanks, resulting from a combination of the cylindrical shape and high rpm, would cause instability that would threaten the spacecraft. To mitigate this problem, a late redesign of the tank baffling was necessary. Finding an acceptable design solution to this third stage tip-off problem has been a major challenge for AACS that has consumed significant resources.

Aerobraking brings with it numerous control problems, especially in contingency mode where the spacecraft attempts to place itself in a safe configuration. During Aerobraking this is difficult because the aerodynamics effects during the drag pass can significantly alter the spacecraft attitude and impart high body rates. During the latter phase of the aerobraking period, the orbital period is so short that the spacecraft is in the drag environment nearly 30% of the time making a recovery effort more difficult, Forces on the spacecraft are sufficiently high to swamp out any control authority of the RWAs, and only thrusters can be used during this period. This has also been an area that has significantly impacted the AACS. Fortunately, except for the modest change to the IMU scale factor, all of the residual MO AACS hardwar c will be used without modification on MGS. '1'here will, however, be substantive changes to the flight software to accommodate the new mission phases and solve the above problems. Present control strategies and configurations appear to provide sufficient margin during the aerobraking period while minimizing fuel usage.

Command & Data Handling Subsystem

A large percentage of the onboard electronics is contained within the Command and Data I Iandling Subsystem's 19 different boxes. All of the MO flight spares arc used with the exception of the Digital Tape Recorders (DTR) which have been replaced on MGS by Solid State Recorders (SSR) to save mass. Modifications to this inherited hardwar c have been made primari l y to address deficiencies identified by the various MO failure review boards. Additional potential single-point-failures were identified during a review of the design for MGS that have also been corrected.

The Standard Control Processor (SCP) uscs a Marconi 281 microprocessor that implements the MIL-STD-1750A instruction set. A discrete implementation of a memory management unit extends the RAM address space an additional 64K page for a total of 128K words (up from MO's 96K). There is 22K of PROM for safe mode recovery and boot routines. Almost al l command and control functions reside within the SCP flight soft ware.

Twelve of the remaining 17 boxes function primarily as Input/Output (1/0) devices to control or command a variety of onboard functions. Addressing is either parallel or serial depending upon the function. The remaining boxes all provide for onboard data handling and deserve a more detailed description.

The Engineering Data Formatter (EDF) provides for the collection, formatting, and distribution, primarily into the downlink data stream, of all onboard engineering telemetry information. It contains its own Marconi 281 microprocessor with 32K RAM and 22K PROM. The EDF has four types of interfaces which are routed t o multiplexers: discrete digital (1/0), analog high level (0-5 V), analog low level (0-32mv) for thermocouples and analog passive (0-5V with a 0.5 mA current source) for Resistive Thermal Devices (1<'11)s).

The Payload Data System (1'11S) provides for the collection, formatting, encoding, and distribution of all science instrument data. It contains an 80C85 microprocessor with 128 Kbytes RAM and 2 4 Kbytes of PROM that controls its functionality. All output data from the PDS is packetized in a CCSDS format, and then Reed-Solomon encoded for error protection.

The Cross-strap Unit (XSU) merges the data paths from the EDF and PDS and arbit.rates under command from the SCP whether data is sent to the downlink or stored on the SSR. Convolutional encoding of the transmitted data stream is also accomplished within the XSU and it also provides necessary control signals to the transponder.

The Solid State Recorder (SSR) is the only unit on the spacecraft that does 1101 USC Grade 1 components, a decision driven by schedule and availability of components. To mitigate this risk, MGS is flying four recorders, while requiring only two functional recorders for the two years of mapping. "l'his requirement derives from the need to record science data simultaneously while playing back previous data onto the downlink during each Deep Space Net (DSN) pass. Two fully independent 750 Mbit data recorders are in each box. Four kilobit (4Kx1) Mitsubishi DRAMs are used foi bulk storage, organized into 16 bit words with six check bits that supports single error correction - double error detection (SECED) with a continuous scrubbing process to remove cosmic ray induced single event upsets. 10 implement a DTR like interface, decode commands, and 10 provide. necessary internal housekeeping tasks, the SSR uses an 80C85 microprocessor with 32 Kbytes of RAM and 30 Kbytes of PROM.

Telecommunications Subsystem

The Telecommunications subsystem provides 22 wat ts of radiated radio-frequency (rf) power at X-band to support a 21,3 kilobits/second downlink data rate at all times in the mission, and up to 85.3 kbps when Mars-earth distance permits, Because MGS must remain nadir-pointed during the entire mapping mission, the High Gain Antenna (I IGA) must be articulated to properly view the earth for high bandwidth communications. To provide the necessary clearance from surrounding structure, tbc antenna on MGS, like MO, is deployed at the end of an articulated boom after the mapping orbit is attained. To reduce power consumption and mass, the 44 watt-rf triivcling-wave-tube-amplifiers (TWTA) used on MO were replaced by 25 watt-rf TWTAs mounted on the 1 IGA. This reduced the DC power required from 100 watts to 60 watts. And with TWTAs mounted on the HGA long waveguide runs from the bus to the HGA were avoided, for a significant mass savings.

Two low-gain transmit and receive antennas (LGA) are used on MGS to assure that for most spacecraft attitudes, it is possible 10 communicate with the spacecraft at low telemetry rates. Unlike, MO, MGS has adopted the policy not to turn-off telemetry during spacecraft maneuvers and critical events, such as propulsion system pressurization. The TWTAs have also been tested to assure their operation during such pyro events.

The transmit LGAs are mounted on the TWTA enclosure on the HGA. l'wo receive LGAs arc on the front (+x) and back of the spacecraft body. When using the HGA m receive commands, the received signal is sent down to the transponders via a coax cable along the boom. Significant work has been expended to assure proper deployment of this boom with its rather large and stiff cable mass. The dynamics of 1 IGA motion at the end of its boom have been thoroughly analyzed and are well understood such that pointing requirements are st i ll met.

Much of the telecommunications hardware is residual from MO, including the X-Band Transponder (MOT) and the Command Data Unit (CDU). This subsystem also includes the Ultrastable Oscillator (USO) which is used for radio science investigations of the Martian atmosphere. included within Telecom is a Ka-Band Link Experiment (KaBLE) that will demonstrate the viability of deep space communications via Ka-band.

Flight Software

The Flight Software (FSW) resides primarily in the SCP and implements the functionality of the spacecraft and instruments. The boot firmware remains essentially unchanged except to accommodate the larger memory address space. The Safe-Mode firmware has changed significantly from MO because of a different spacecraft architecture, and the addition of aerobraking associated mission modes and configurations, The hardware would not accommodate any expansion in PROM space, so significant scrubbing of functions were required to obtain the minimum necessary functionality for MGS. 'J'here arc, however, major blocks of PROM code that remain unchanged from MO.

The SCP software also benefits from significant MO inheritance. At this point in the development, the claim is that 80% of the code will remain unchanged, though it is still too carfy to test the validity of this assertion, and its implication relat ive to a limited program of software testing planned for MGS.

The PROM code in the EDF required changing because of different telemetry tables to accommodate a different spacecraft. The PDS code, however, remains unchanged from MO in a conscious effort to minimize cost. The bandwidth allocated to the two deleted science instruments will simply remain unused.

The "Faster, Better, Cheaper" Paradigm

The MGS Project Office and our coat ractors have made a conscious effort to implement a "faster, better, cheaper" paradigm. However, MGS may not be the ideal vehicle for an evaluation of such a new way of doing business since it has so much inheritance from the earlier epoch. Nevertheless, wc have made a serious effort to evaluate every decision on the basis of whether what wc arc doing is simply habit as a result of our prior culture, or whether the selected course of action returns value to the Project comparable to the investment of resources.

Examples of new ways of doing business include:

Electronic mail and communications is used in place of paper. While wc have not been able to entirely suppress the need for paper, a large percentage of our written communications is by computer file. Reviews arc conducted using computer driven projectors to replace the ubiquitous overhead projector with the transparent foils simply projections of slides from a computer file,

Macintosh is the standardized platform for all Project documentation and communications. Softwa c and version uniformity across the Project has also been implemented to facilitate rapid and efficient communications between team members.

Collocation of Project team members. There is also a streamlined Project staff organization that mirrors the contractor's organization in area of responsibilities and functions. This allows efficient communications between Pasadena and Denver at all levels of management, Furthermore, JPL tries to approach its system contractor as a team member rather than a monitor, contributing where possible to the everyday work towards a successful project.

Collaborative servers at Pasadena and Denver update each other every half-hour allowing both organizations to share information in while in process. Electu onic mail systems at the two facilities have a transparent interface — sending eMail to a Denver colleague is as simple and efficient as to one here at JPL.

Both organizations maintain a lean team to control costs and keep comm unication paths short.

Design reviews arc conducted informally, reduced in content, shortened in time, wilh fewer board members (sometimes with no real board al all), with action items documented simply and handled as expeditiously as possible. Review board members tend more toward peers with directly applicable engineering experience than managers.

1 Iardware retest prior to delivery 10 I.MA in Denver was consciously avoided where the item was fully certified for flight on MO and bad been properly stored since that time. ‘1’here was resistance to this strategy initially, as it ran counter to the culture of both organizations, but to date it has not been a problem. After wc complete Assembl y, Test, and Launch Operations (ATLO) activities, we will reassess the effectiveness of this cost saving strategy for future application.

This spacecraft will be launched essentially without any flight spare hardware. If any hardware box fails, it must be removed from the spacecraft and repaired. Some of the prime-rcdundanl subassemblies reside in a single box (an inheritance from MO where a full complement of spares was available), so removal of those boxes will bring the spacecraft system down completely. Rapid repair kits have been assembled for most boxes to minimize turn-around time, but the fact still remains that a failure near launch may involve launching with an unplanned sing] e-point-failure or jeopardize launch within the ’96 window to support a repair. Such a decision would not be taken lightly, as most all of the engineering subs ystem boxes require major disassembly of the spacecraft bus for removal. Simply the process of removal, repair and then reassembl y places other hardware at risk, as well as the comprehensiveness of any subsequent retesting prior to launch.

The significant inheritance from MO has saved the Project significant resources and time, and represents the only possible way a mission and spacecraft of this complexity and quality could have been assembled on such a short schedule. 1 lowever, onc important lesson in retrospect is that inheritance of flight hardware must be accompanied with an inheritance o f skilled people, knowledgeable of the details of the hardware design and its application to the mission. It is quite evident as an observer of the activities across the Project, and onc who did not work MO, that those individuals that continue to contribute the most 10 MGS arc those with prior MO experience. Attracting and holding the interest of such individuals has been difficult.

CONC1.US1ON

With only a year to go before the MGS launch window opens on November 5, 1996, most of the engineering subsystem hardware has been delivered to Lockheed-Martin Astronautics in Denver for spacecraft integration, System testing has just begun. Project reserves arc healthy, people are dedicated to the success of this mission, and the hardware has been performing well to date. There is a “can do” spirit about all those working on MGS and a mood of optimism pervades that says, “yes, wc arc going to be successful!”

ACKNOWLEDGMENTS

The work described in this paper has been performed by the Jet Propulsion laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.